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THE ROLE OF MICROSTRUCTURE ON VARIOUS STAGES OF THE VERY HIGH CYCLE FATIGUE BEHAVIOR OF AN a + ß TITANIUM ALLOY, TI-6Al-2Sn-4Zr-6Mo (PREPRINT)

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Metals Branch
Metals, Ceramics & Nondestructive Evaluation Division

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14. ABSTRACT
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The role of microstructure on various stages of the very high cycle fatigue behavior of an α + β titanium alloy, Ti-6Al-2Sn-4Zr-6Mo

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ABSTRACT

The very high cycle fatigue behavior (10^5-10^9 cycles) of Ti-6246 has been investigated using ultrasonic fatigue techniques. In this regime of fatigue (0.4-$0.6\sigma_{YS}$), only certain microstructural regions are susceptible to fatigue damage accumulation, and lifetimes are related to the distribution of fatigue critical microstructural neighborhoods. Three distinct categories of crystallographic crack initiation sites have been identified. Fatigue crack initiation and early growth is typified by a crystallographic facet formation process within α_p grains favorably oriented for basal slip in microtextured regions of the microstructure. However, many microtextured regions are observed throughout the microstructure and it is not clear why some of these regions are susceptible to fatigue damage accumulation while others are not. To identify the influence of microtexture on the small fatigue crack growth process, FIB notches were machined in fatigue specimens to serve as fatigue crack initiation sites in various microstructural neighborhoods. Regions with a texture favorably oriented for basal slip were observed to promote early fatigue crack initiation from FIB notches. However, small fatigue crack propagation rates did not correlate with the locally measured textures in individual microtextured regions.

KEYWORDS

Ultrasonic fatigue, Ti-6Al-2Sn-4Zr-6Mo, fatigue crack initiation, small fatigue crack growth, microtexture.

INTRODUCTION

The very high cycle fatigue (VHCF) behavior of many structural alloys presents a unique opportunity to identify specific microstructural regions that accumulate local plasticity while other microstructural neighborhoods experience nominally elastic loading. The occurrence of failures at these stresses, below the endurance limit, is attributed to cyclic irreversible strain accumulation [1]. Since the maximum stress imposed on components in this regime is below the bulk yield stress, localized plasticity in specific microstructural neighborhoods resulting from microstructural heterogeneities is presumed to produce the observed variability in fatigue behavior.

Conventional wisdom of fatigue in alpha + beta titanium alloys maintains that fatigue cracks initiate in the α_p phase [2] since the slip length is maximized in large ideally-oriented α_p grains. Hall [3] presents a methodology for interpreting these results by introducing the term crack like discontinuity (CLD) which can be related to the α_p grain size, α colony size, prior β grain size, or the size of microtextured regions. The variability in total fatigue lifetime can be constructed as a summation of the variability observed in each of the individual regimes of the fatigue failure process (i.e. fatigue crack initiation, small fatigue crack growth, long fatigue crack growth) after Hall.[3] Specific microstructural features will have a variable influence on each of these individual regimes of fatigue failure. For example, a microstructural location that exhibits high resistance to fatigue crack initiation (i.e. a fine grain neighborhood with random texture) would likely exhibit accelerated long fatigue crack growth rates.

In the case of wrought titanium alloys, fatigue crack initiation is driven by local crystallographic orientations as opposed to the presence of pores or intermetallic particles. Microtexture is known to strongly affect fatigue behavior in α+β titanium alloys [4-8]. In the regime of VHCF, it has been previously reported that fatigue crack initiation sites are microtextured regions and the majority of α phase material (lath α and equiaxed α_p) is oriented for slip on basal and prism planes. LeBiavant et al. observed that microtextured regions facilitate the formation of multiple fatigue cracks, which coalesce to form a propagating fatigue crack in this class of alloys. In other work [5], evidence of fatigue cracks is observed in numerous microtextured regions, however the size of microtextured regions is cited as the critical variable affecting fatigue behavior since fatigue cracks are presumed to propagate more easily in favorably oriented microtextured regions. In summary, microtexture is known to affect fatigue performance in titanium alloys due to the anisotropic mechanical response of these local neighborhoods. The objective of this work is to determine the role of microtexture on both fatigue crack initiation mechanisms and small fatigue crack growth.

MATERIAL AND EXPERIMENTAL PROCEDURE

The material used in this study is an α+β titanium alloy, Ti-6Al-2Sn-4Zr-6Mo, which has been characterized and documented elsewhere [8]. As shown in Figure 1, the α_p grain size is approximately 4 μm in diameter and the transformed β regions are approximately 20 μm in diameter. Fatigue tests have been completed at 20 kHz at R=0.05 and room temperature.

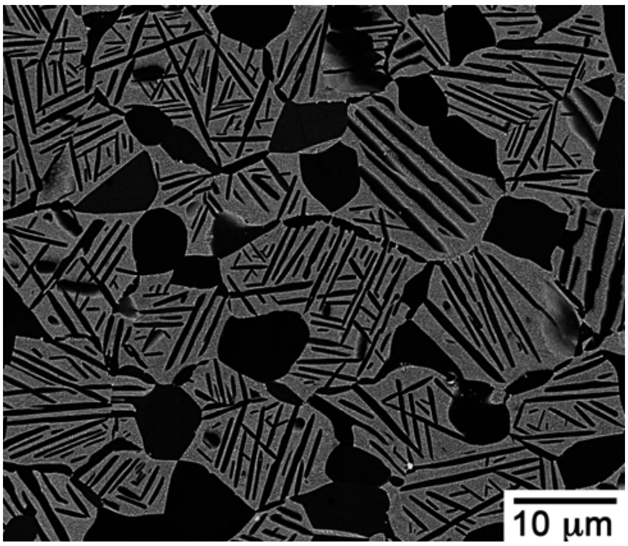

Figure 1. A secondary electron (SE) micrograph of the duplex microstructure in the material used in this study.

Characterization of fracture surfaces has been completed using an FEI XL30 FEG scanning electron microscope. The crystallographic orientations of the grains within the crack initiation neighborhood were determined using an EBSD detector manufactured by EDAX-

TSL. The material at the site of fatigue crack initiation was investigated with OIM to determine the specific crystallographic deformation mechanisms active in the fatigue crack initiation process.

The effect of microstructure on small fatigue crack growth was studied using notches on the order of 20 μm, which were machined using the focused ion-beam (FIB) microscope. In each specimen, multiple FIB micronotches were machined to enable direct comparison of the susceptibility of each microstructural neighborhood to fatigue damage. Additionally, the local microstructure surrounding these notches was characterized via EBSD. Testing was interrupted every 2,000-3,000 cycles so that acetate replicas could be made of the specimen surface to measure surface crack length. Further experimental details can be found elsewhere.[9]

RESULTS AND DISCUSSION

The fatigue lifetimes observed were in the range of 10^5-10^9 cycles, and at specific stress levels, scatter of up to three orders of magnitude was observed. Surface initiated failures typically are associated with shorter lifetimes, while subsurface initiated cracks lead to longer fatigue lifetimes. However, observed lifetimes overlap between surface initiated and subsurface initiated fatigue cracks.

Fatigue crack initiation sites

Each of the three characteristic fatigue crack initiation sites exhibited faceted fracture of α_p grains as shown in Figure 2. Figures 2(a) and 2(b) illustrates an initiation mechanism where facet form predominantly in α_p grains at the specimen surface and subsurface, respectively. Figure 2(c) illustrates an initiation site characterized by facet formation across both α_p and lath α along the same macroscopic plane. It was determined that α_p facets are oriented to maximize the resolved shear stress indicating that they form through a slip process. The corresponding inverse pole figures (IPFs) measured locally at each of the characteristic fatigue crack initiation sites are shown below the micrographs in Figure 2. The IPFs are classified according to the deformation mode most likely to be activated in these local microstructural regions (i.e. basal, prism) and the numbers listed correspond to the maximum texture intensity within these regions. Surface initiation sites are associated with a texture suitable for easy basal slip. Subsurface initiation sites typically have favorable orientations for both basal and prism slip, although some initiation sites exhibited a more random texture as shown in Figures 2(b) and (c), respectively. As reported elsewhere, microtextured regions are commonly observed in nominal microstructural regions as well as at fatigue crack initiation sites.[8] Thus, the presence of favorable oriented microtextured regions is a necessary, but not a sufficient condition for fatigue crack initiation. Significantly, aside from the aforementioned preference for surface initiation sites to exhibit shorter lifetimes, no correlation between local texture and lifetime was observed.

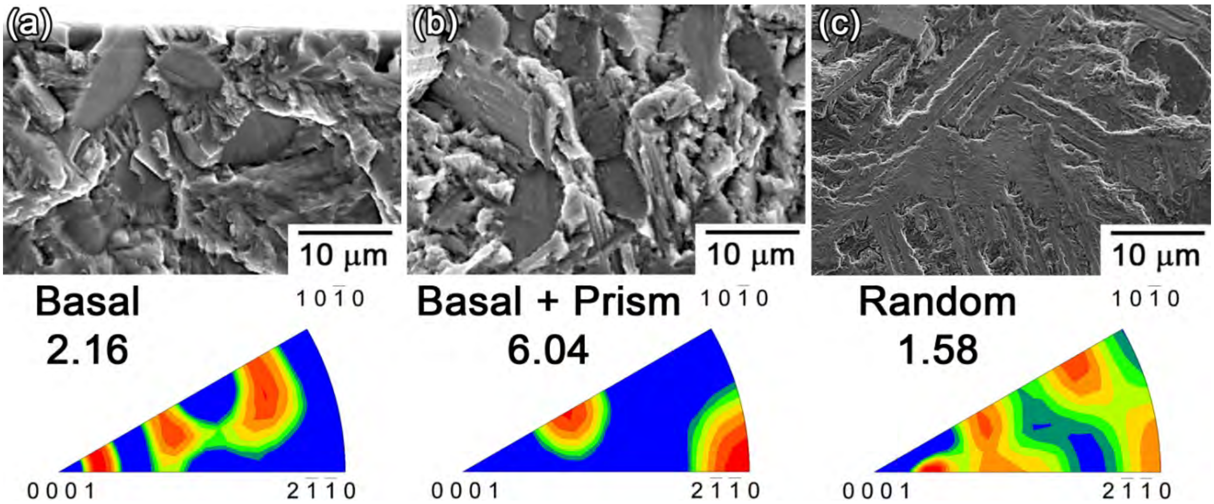

Figure 2. Fractographs and corresponding loading direction inverse pole figures (IPFs) of the three characteristic crack initiation sites (a) surface (b) subsurface and (c) subsurface macroscopically planar initiation sites.

Fatigue crack growth behavior

The small fatigue crack growth rates measured in this study are presented in Figure 3, which displays both the (a) 2c vs. N plot and the (b) da/dN vs. ΔK plot. The data in Figure 3(a) represent individual measurements from acetate replicas for each of the cracks in a single specimen. From this plot, it is clear that the local neighborhoods surrounding the notches exhibited different lifetimes to initiation and that the subsequent small crack growth was variable with some cracks exhibiting periods of crack arrest while others continued to propagate.

The solid curve shown in Figure 3(b) is a prediction of the long crack growth curve for specimens at R=0.05 based on testing from C-T specimens at other stress ratios.[10] Using the lower end of this curve as a long fatigue crack threshold, a clear small crack effect is observed in the data. As the cracks from these micronotches propagate beyond approximately 5 MPa $m^{1/2}$, they converge to a uniform continuum growth rate. The scatter in growth rates for these cracks is limited to the small crack regime.

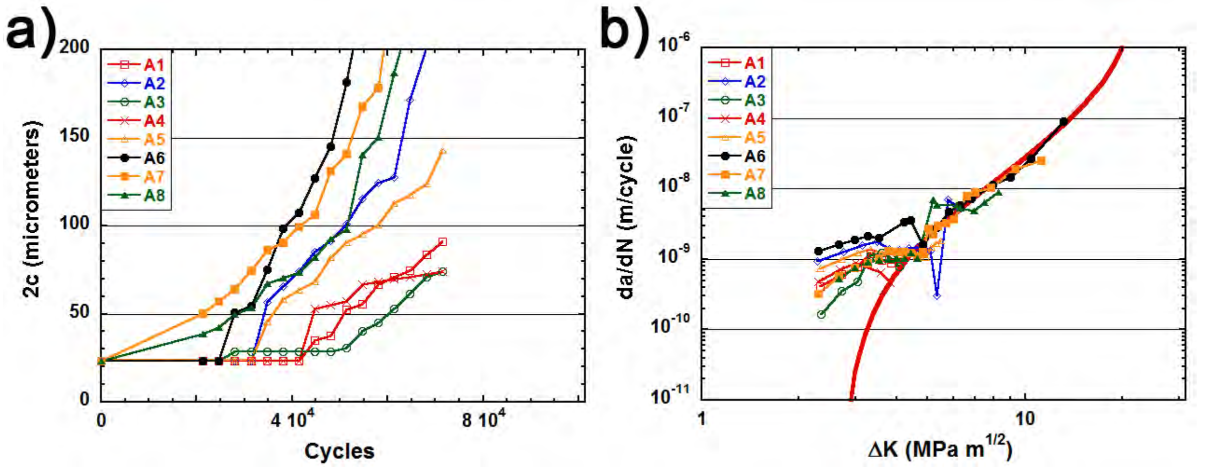

Figure 3. Small fatigue crack growth rates measured with ultrasonic fatigue techniques illustrate a small crack effect, but merge with long crack growth predictions as they continue to propagate.

In Figure 4, the small crack propagation lifetimes have been plotted and these lifetimes represent the number of cycles required for an initiated crack to propagate to a surface length of 75 μm. This is not to say that cracks only exhibit a small crack effect up to 75 μm, rather the number was selected since even the smallest cracks grew to a surface length of approximately 75 μm. The lifetimes were calculated by fitting a power law equation to the crack growth curves shown in Figure 3(a) and then extrapolating the curve down to the notch size to determine the lifetime to initiation. As Figure 4 illustrates, there is not much scatter in the small fatigue crack propagation lifetimes. The inverse pole figures (IPFs) shown in Figure 4 are calculated from the microstructural neighborhoods surrounding the micronotches that initiated cracks representing the full spectrum of growth rates. A few IPFs are included in Figure 4 to describe the grain orientations adjacent to the FIB notches. These IPFs were calculated from measurements of a 65 x 95 μm region surrounding the FIB notches. These IPFs are all plotted with the same maximum value of 5 times random and the individual maxima are listed next to the corresponding IPF. Each IPF illustrates a significantly different local texture and intensity, yet the propagation lifetimes are within an

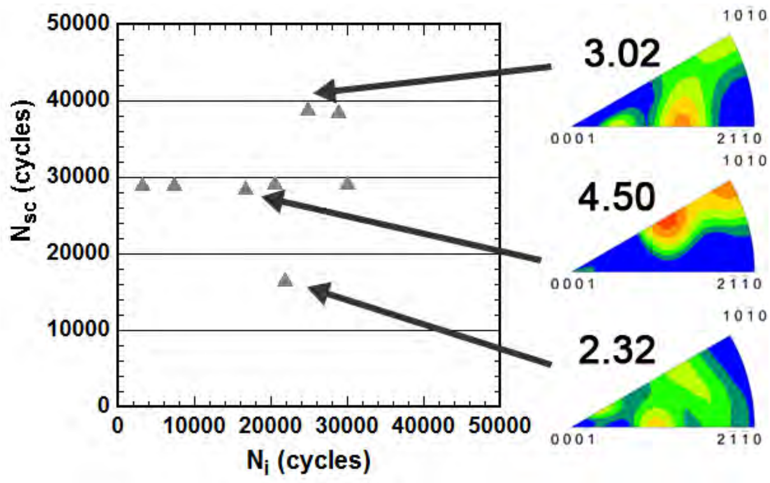

Figure 4. This plot illustrates the small amount of scatter measured in the small fatigue crack propagation. This is plotted as a function of initiation lifetime to illustrate that no relationship exists between initiation lifetime and propagation lifetime. The loading direction IPFs shown indicate that neighborhoods with significantly different textures exhibited similar propagation lifetimes.

order of magnitude. It is not possible to identify representative local textures for correlation with average propagation lifetimes. Therefore, these three IPFs are included to illustrate the point that similar propagation lifetimes can be achieved via a range of different local textures. The absence of a correlation between propagation lifetime and local texture indicates that other microstructural characteristics, for example microstructural morphology (lath α vs. equiaxed α_p) or local volume fraction of α_p may have a more significant influence on crack propagation behavior. Further details on this can be found elsewhere.[9]

SUMMARY AND CONCLUSIONS

In this paper, it was shown that fatigue crack initiation sites in the fine grain duplex microstructural condition of Ti-6Al-2Sn-4Zr-6Mo are characterized by the presence of microtexture where the preferred texture is suitable for basal and prism slip. Relative to the scatter in total fatigue lifetime variability, very little scatter is expected to result from variability in small fatigue crack growth. Furthermore, no systematic variation in small crack growth rates was demonstrated with respect to the investigated microstructural parameters. This indicates that the majority of the scatter in fatigue lifetimes results from the inherent variability in the fatigue crack initiation process.

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